Physics 417/517 Introduction to Particle Accelerator Physics

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Equilibrium Energy Spread

Quantized photon emission events act to stimulate motion in all three degrees of freedom. Thus, the oscillations do not damp to zero.

$$\left\langle \Delta A^2 \right\rangle = \left\langle A_1^2 - A_0^2 \right\rangle = \Delta e^2 \qquad \Delta e = \hbar\omega$$

$$\left\langle \frac{dA^2}{dt} \right\rangle = \int_0^\infty \Delta e^2 \frac{d\dot{n}}{d(\Delta e)} d\Delta e = \dot{N}_{ph} \left\langle \Delta e^2 \right\rangle$$

In equilibrium.

$$\left\langle A^2 \right\rangle = \frac{\tau_{\Delta\phi}}{2} \dot{N}_{ph} \left\langle \Delta e^2 \right\rangle$$

$$\frac{\sigma_E^2}{E^2} = \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2} \frac{\gamma^2}{2+\vartheta} \frac{\left\langle 1/\rho^3 \right\rangle}{\left\langle 1/\rho^2 \right\rangle}$$

Equilibrium Emittance

$$\left\langle \delta a^2 \right\rangle = \frac{\Delta e^2}{E_o^2} H(s)$$

$$H(s) = \beta D'^2 + 2\alpha D D' + \gamma D^2$$

In equilibrium, averaged over the ring.

$$\left\langle a^2 \right\rangle = \frac{\tau_x}{2} \dot{N}_{ph} \left\langle \Delta e^2 \right\rangle$$

$$\varepsilon_x = \frac{\sigma_x^2}{\beta_x} = \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2} \frac{\gamma^2}{1-\vartheta} \frac{\left\langle H / \rho^3 \right\rangle}{\left\langle 1/\rho^2 \right\rangle}$$

Emittance and energy spread increases

For recirculated linacs, there is no equilibrium and similar estimates are used to compute emittance and energy spread increases (for a bend of π = 180°)

$$\Delta\varepsilon_{x,y} = \frac{1}{2cE_0^2}\int \dot{N}_{ph}\left(e^2\right)H\left(s\right)ds = \frac{55C_\gamma \hbar c\left(mc^2\right)^2}{64\pi\sqrt{3}}\gamma^5\int\frac{H}{\rho^3}ds$$

$$\Delta\frac{\sigma_E^2}{E^2} = \frac{5\pi}{32\sqrt{3}}\frac{\hbar c}{mc^2}\frac{\gamma^2}{2+\vartheta}\left(11-\frac{64}{25}\right)\frac{\left\langle 1/\rho^3\right\rangle}{\left\langle 1/\rho^2\right\rangle}$$

$$= \frac{5\pi}{32\sqrt{3}}\frac{\hbar c}{mc^2}\frac{\gamma^2}{2+\vartheta}\left(11-\frac{64}{25}\right)\frac{\left\langle 1/\rho^3\right\rangle}{\left\langle 1/\rho^2\right\rangle}$$

Independent Orbit Recirculators - Motivation

- At final beam energy, $E_f \sim$ several 100 MeV, cost of racetrack microtron is dominated by cost of end magnets

- Cost of end magnets $\propto E_f^3$

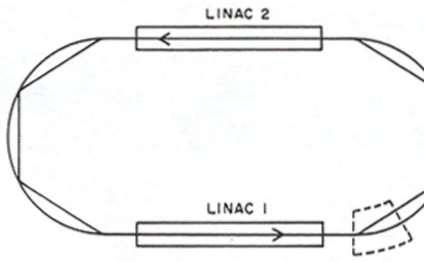
  $\Rightarrow$ Standard racetrack microtron (RTM) uneconomical at $E_f \approx 500 - 1000$ MeV

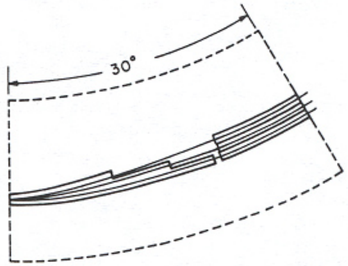
- Bicyclotron and hexatron: one method to overcome the problem but they are similarly limited

- A distinctly different approach: A recirculation system with independent or separate orbits, *i.e.* orbits which do not share the same uniform field magnets

The “Mesotron”

- The first of independent orbit recirculating accelerator designs
- Proposed by Bathow et al., (1968) for high duty factor acceleration at very high energies – up to 60 GeV

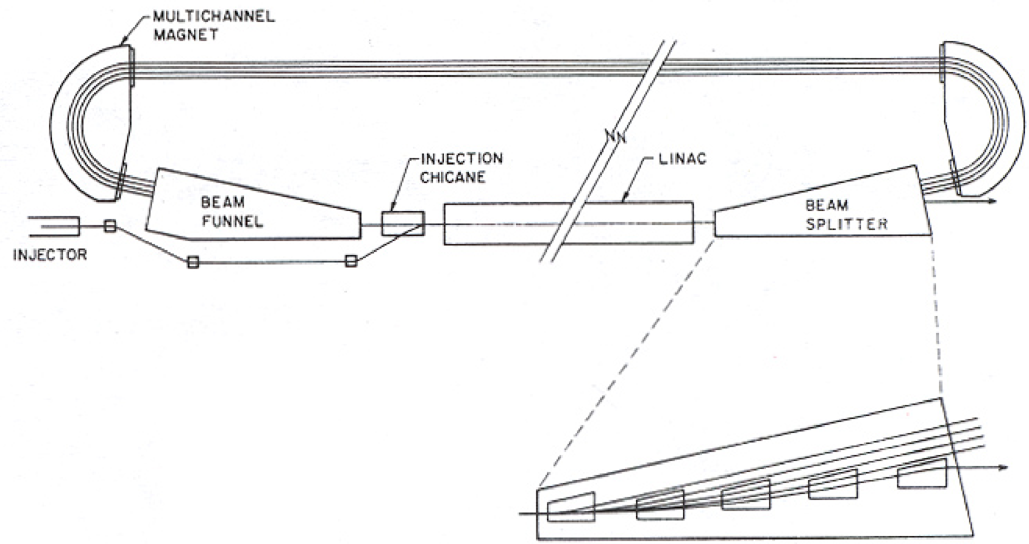




- Although looks similar to a high order polytron, it is distinctly different because of the independent control of every orbit
- At high energies, synchrotron radiation (SR) could present problems and magnetic field values would be restricted to very low values as a consequence.
- At E > 50 GeV, the Mesotron might be cheaper to build than a synchrotron since it has independent DC magnets and can tolerate a much greater energy loss per orbit by SR.

The Stanford–HEPL Superconducting "Recyclotron"

- Main recirculation magnets incorporate four channels (tracks) in which the uniform fields are independently tailored to the momenta of the separate orbits.
  - Use a constant magnet gap with staggered coil windings which produce an appropriately stepped field profile.



No Phase Stability in Independent Orbit Recirculators

- For isochronous ($M_{56} = 0$) transport:

$$\begin{pmatrix} \Delta\phi_{l+1} \\ \Delta E_{l+1} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -eV_c \sin\phi_s & 1 \end{pmatrix} \begin{pmatrix} \Delta\phi_l \\ \Delta E_l \end{pmatrix}$$

- Usually ϕ_s =0. Higher order effects tend to become important.

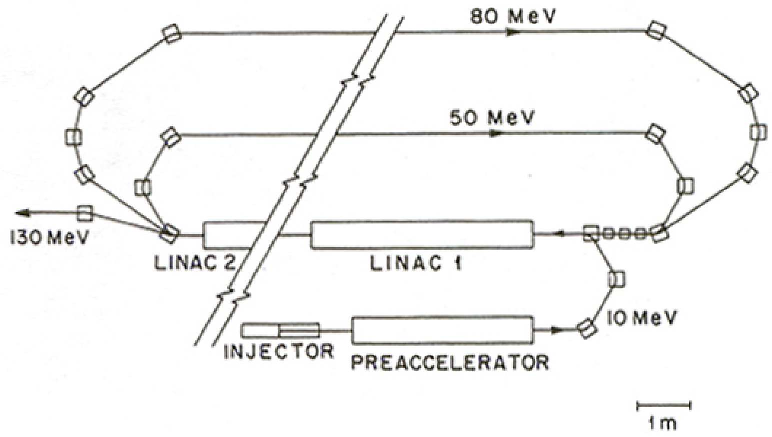
Examples of Isochronous Recirculating Linacs

- The Wuppertal/Darmstadt “Rezyklotron”
- The MIT-Bates Recirculator
- The CEBAF at Jefferson Lab

The Wuppertal/Darmstadt "Rezyklotron"

- The "Rezyklotron" incorporates a superconducting linac at 3 GHz.
- Beam injection energy = 11 MeV, variable extraction energy up to 130 MeV, beam current 20 μA, 100% duty factor. Energy resolution = 2 x 10^{-4} .
- Two orbits designed with 180^0 isochronous and achromatic bends and two quadrupole doublets and two triplets in the backleg.
- Isochronous beam optics

  Phase oscillations do not occur and energy resolution is determined primarily by second order effects in the linac.



The MIT-BATES Recirculator

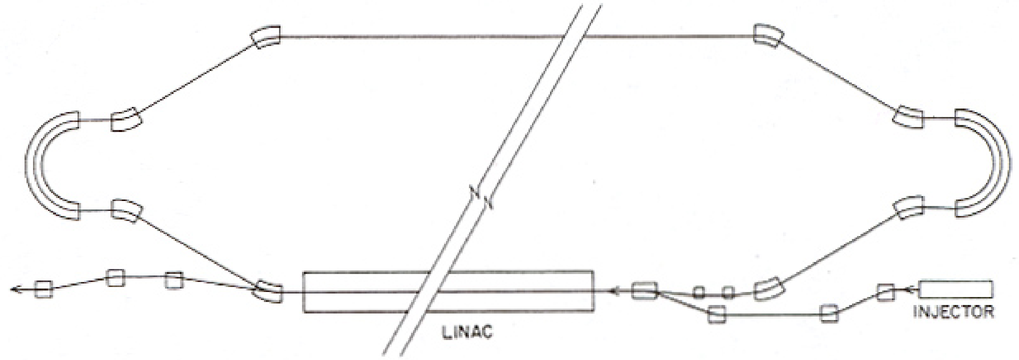
- The MIT-Bates, one-orbit recirculator: An isochronous recirculator
- Severe transient beam loading dictates the isochronous nature of MIT-Bates transport system.

  a) Fluctuations of beam current during each pulse cause variable beam loading The resulting first pass energy variation of ± 0.15%. At a magnet bending radius of about 1m this energy fluctuation would result in bunch length, after recirculation in a non-isochronous orbit, of almost 90° of rf phase!

  b) Total accelerating potential drops by 6% when recirculated beam re-enters the linac and total beam current goes from 8mA to 16 mA. With non-isochronous transport, resulting change in orbit energy would be equivalent to a path length change of many λ_{rf} .
- Both effects were eliminated by an isochronous recirculation design that could accommodate a 6% energy change.
- Flanz *et al*. (1980) successfully designed a recirculator that satisfies all these conditions.

The MIT-BATES Recirculator (cont'd)

- Injection energy = 20 MeV
- Each end of the transport system consists of 5 uniform field dipole magnets which bend by 20°, –20°, 180°, –20° and 20°.
- Edge focusing in these magnets is the only form of focusing in these parts of the orbit.
- Four sextupoles control higher order optical aberrations
- Straight section in the backleg contains 5 quadrupole triplets
- Final energy to date is 750 MeV (?) at an average current of 100 μA (?) (5 mA pulse current) with energy resolution ±0.15% have been achieved.



The CEBAF at Jefferson Lab

- The CEBAF accelerator is a 5-pass recirculating srf linac with cw beams of up to 200 μA, geometric emittance < 10^{-9} m, and relative momentum spread of a few 10^{-5}.

- The present full energy is nearly 6 GeV. An upgrade to 12 GeV is planned.

The CEBAF at Jefferson Lab (cont'd)

- Most radical innovations (had not been done before on the scale of CEBAF):
  - choice of srf technology
  - use of multipass beam recirculation
- Until LEP II came into operation, CEBAF was the world's largest implementation of srf technology.